Balloon Observation of the X-ray Spectrum of the Crab Nebula above 15 Kev*

George W. Clark

Department of Physics

and

Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, Massachusetts

A concentrated source of cosmic x-rays with energies above 15 Kev has been observed in a balloon flight conducted on July 21, 1964. The sky was scanned with a directional x-ray detector rotating about a vertical axis, and a peak in the counting rate occurred when the Crab Nebula was within the field of view of the detector. Since the Crab Nebula is known to emit x-rays near 4 Kev,(1) it is probable that the higher energy x-rays observed in this experiment came from the same object. Assuming this to be the case, the data yield an approximate determination of the x-ray spectrum of the Crab Nebula in the energy range from 15 Kev to 60 Kev.

The x-ray detector was a scintillation counter employing a NaI(Tl) crystal 97 cm^2 in area and 1 mm thick. A collimator of brass slats gave a field of view $\pm 16^{\circ}$ wide in one direction and $\pm 55^{\circ}$ wide in the other. A mu-metal shield and a layer of 1/16 inch lead sheet covered the sides and back of the photomultiplier. The pulses were fed to a 5-channel differential

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pulse height analyzer and scaler. The indicator lights from the scalers were photographed on a moving film together with the indicator lights of a scaler driven by a crystal controlled oscillator which provided the time base of the experiment. The apparatus was suspended so that the detector axis was inclined at 35° to the vertical, and the $\pm 16^{\circ}$ direction of the field of view was horizontal. The payload was rotated by a line twister which had a period of 9.3 minutes. The azimuth of the detector axis was determined every 20 seconds from a magnetometer reading, and intermediate values were obtained by interpolation.

The detector was calibrated with 25 and 65 Kev x-rays. At both energies the distributions in height of pulses going into the 5-channel analyzer had half-widths at half-maximum of 37%. Using the centers of these pulse height distributions as calibration standards we adjusted the discriminators to record pulses of the average size produced by 9-15 Kev x-rays in channel I, 15-28 Kev in channel II, 28-42 Kev in channel III, 42-62 Kev in channel IV, greater than 62 Kev in channel V. The energy loss of a minimum ionizing particle traversing the crystal was greater than 600 Kev so that most pulses produced by charged cosmic rays were recorded in the fifth channel only.

The balloon was launched at dawn from Palestine, Texas. It reached a maximum pressure altitude of 2.9 mb about 3 hours before the meridian transit of the Crab Nebula, and then gradually descended, passing below 5 mb near the time transit.

In order to search for x-ray emission from a specific object with maximum sensitivity it was necessary to combine the data from many rotations,

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taking into account the diurnal motion of the object. This was done by tabulating separately the number of counts and the exposure time for each interval of relative azimuth measured from the object, and then dividing the total counts by the total exposure time to find the average counting rate in each of the intervals of relative azimuth. When this procedure was applied for the case of the Crab Nebula to the data obtained at pressure altitudes above 3.9 mb it gave the results summarized in Figure 1. During this 80 minute period of observation the zenith angle of the Crab Nebula decreased from 35° to 18°, and its azimuth increased from 96° to 118° from geographic north. Distinct peaks in the counting rates are seen in channels II, III and IV at a relative azimuth about 10° greater than that which would be expected for a peak due to the Crab Nebula if the error in determining the magnetic azimuth were negligible. Inspection of the payload and calibration of the magnetometer indicated the presence of systematic errors in the magnetic azimuth determination that are large enough to account for the discrepancy.

The shape of a peak due to a concentrated source was measured in the laboratory by suspending the payload as in flight and rotating it uniformly past the direction of an artificial 25 Kev x-ray source mounted above it. The expected peak shapes for a source at a zenith angle of 30° are indicated in Figure 1. Also indicated for each peak is the number of standard deviations by which the combined counting rate in the central three intervals exceeds the grand average around the entire circle. The probability of these peaks occurring by statistical fluctuation is negligible, and it seems necessary to conclude that they are caused by a source of x-rays in a direction near and, most likely, coincident with the Crab Nebula.

Information concerning the spectrum of the observed x-rays can be obtained from the data provided that proper allowance is made for absorption in the atmosphere. Assuming that the source is the Crab Nebula one can calculate the thickness of the atmosphere along the line of sight. When a given object crosses the center line of the rectangular field of view the expected counting rate of pulses with sizes in the interval from H_1 to H_2 can be expressed by the formula

$$R = A(\theta) \int_{H_1}^{H_2} dH \int_{0}^{\infty} j(E) \exp\left[-\mu_{air}(E)x\right]\left\{1 - \exp\left[-\mu_{NaI}(E)t\right]\right\} \quad (1)$$
$$\times \left(1/\sigma\sqrt{2\pi}\right) \exp\left[-(E-H)^2/2\sigma^2\right] dE,$$

in which $A(\theta)$ is the projected area of the detector in a direction lying on the center line at an angle θ from the detector axis, $j(E)dE$ is the intensity of x-ray photons with energy E in dE, μ_{air} (E) and μ_{NaI} (E) are the mass absorption coefficients at energy E of air and sodium iodide respectively, x is the thickness of the atmosphere along the line of sight, and t the thickness of the sodium iodide crystal. In this expression the energy resolution of the detector is represented by a gaussian response function with a standard deviation σ.

The differences between the average background counting rates and the average peak rates observed as the source crossed the field of view were determined for each of the five pulse height channels during the portion of the flight when the atmospheric thickness along the direction to the

Crab Nebula was between 3.5 and 4.0 g cm^{-2}. These differences, which are the counting rates attributable to the Crab Nebula, are shown in Figure 2. The lines join the expected values calculated for three assumed incident differential number spectra given by the formula

$$j\ (E) = j_o(E/E_o)^{-\alpha-1} \qquad (2)$$

with α = 1, 2 and 3, and normalized to the observed value in channel III. The best fit for channels II, III and IV is obtained with α = 2. No peaks were observed in channels I and V for which only upper limits are indicated in the figure. It is evident that the spectral index above 60 Kev is greater than 2.

The flux density $I(\nu)$, which is the energy incident per unit area, per unit time and per unit frequency interval, is related to the number spectrum by the formula

$$I(\nu) = Ej(E)h \qquad (3)$$

where $h = dE/d\nu$ is Planck's constant. Taking α = 2 and adjusting the constants j_o, E_o to fit the rates observed in channel III one finds for the flux density the expression

$$I(\nu) = I_o(\nu/\nu_o)^{-2} \qquad (4)$$

where

$$I_o = (2.4 \pm 0.6) \times 10^{-27}\ \text{ergs cm}^{-2}\ \text{sec}^{-1}\ (c/s)^{-1}$$

and $\nu_o = 7.2 \times 10^{18}$ c/s

over the range from 5.0×10^{18} to about 1.0×10^{19} c/s, corresponding to the energy range from 20 Kev to 40 Kev. This result is plotted in Figure 3 together with an upper limit of 1.2×10^{-28} ergs cm^{-2} sec^{-1} $(c/s)^{-1}$ at $\nu = 2 \times 10^{19}$ c/s ($\sim$80 Kev) derived from the negative result in channel V. Also shown is a summary of the previous data on the electromagnetic spectrum of the Crab Nebula. The spectrum in the radio and optical regions was taken from the recent review of Moroz.[2] The optical portion is subject to considerable uncertainties due to poorly known corrections for interstellar absorption. The spectrum from 3×10^{17} to 10^{18} c/s was computed from data of the NRL group.[3]

The results of this experiment are new evidence against the idea that the x-rays from the Crab Nebula are the blackbody emission from the surface of a neutron star. Previously, the observation of a gradual lunar occultation by Bowyer et al.[4] indicated that the source was not an unresolvable point as expected for any star, but rather an extended object with an angular diameter of about 1 arc minute. Now, in addition, in order to explain the x-ray intensity above 15 Kev observed in this experiment it would be necessary to assume a surface temperature of more than 6×10^7 K° which is considerably greater than the theoretical limit of 1.6×10^7 K° derived by Morton from an analysis of the effect of neutrino processes in the core on the rate of cooling.[5] On the other hand, the data above 15 Kev can be reasonably well fitted to an incident spectrum of radiation emitted in free-free transitions in a hot gas near 2×10^8 K°.

The apparatus for this experiment was constructed by Mr. William B. Smith. His assistance throughout is gratefully acknowledged. The balloon operation was carried out under the direction of the National Center for Atmospheric Research. The data was processed by Mr. Alfred Wan with the facilities of the MIT Computation Center. I wish to thank Dr. H. Friedman for permission to include the recent data of the NRL group in Figure 3.

Figure Captions

Figure 1. Average counting rates in the five pulse height channels *versus* the magnetically determined azimuth relative to that of the Crab Nebula. The peak near 0° in channels II, III and IV is attributed to the x-ray source in the Crab Nebula. The cause of the variations in channel I is not known, and may be instrumental.

Figure 2. Peak minus background counting rates from the observed source for the five pulse-height channels. Upper limits only are indicated for channels I and V. The dashed, solid, and dotted lines represent the expected variation in counting rates for incident spectra in the form of power laws with spectral indices of 1, 2 and 3 respectively, and normalized to the observed rate in channel III.

Figure 3. Summary of data on the spectrum of electromagnetic radiation from the Crab Nebula.

References

(1) S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman, Nature, 201, 1307 (1964).

(2) V. I. Moroz, Soviet Astr. J. 7, 755 (1964).

(3) H. Friedman, private communication.

(4) S. Bowyer, E. T. Byram, T. A. Chubb, and H. Friedman, Science, 146, 912 (1964).

(5) D. C. Morton, Ap. J., 140, 460 (1964).

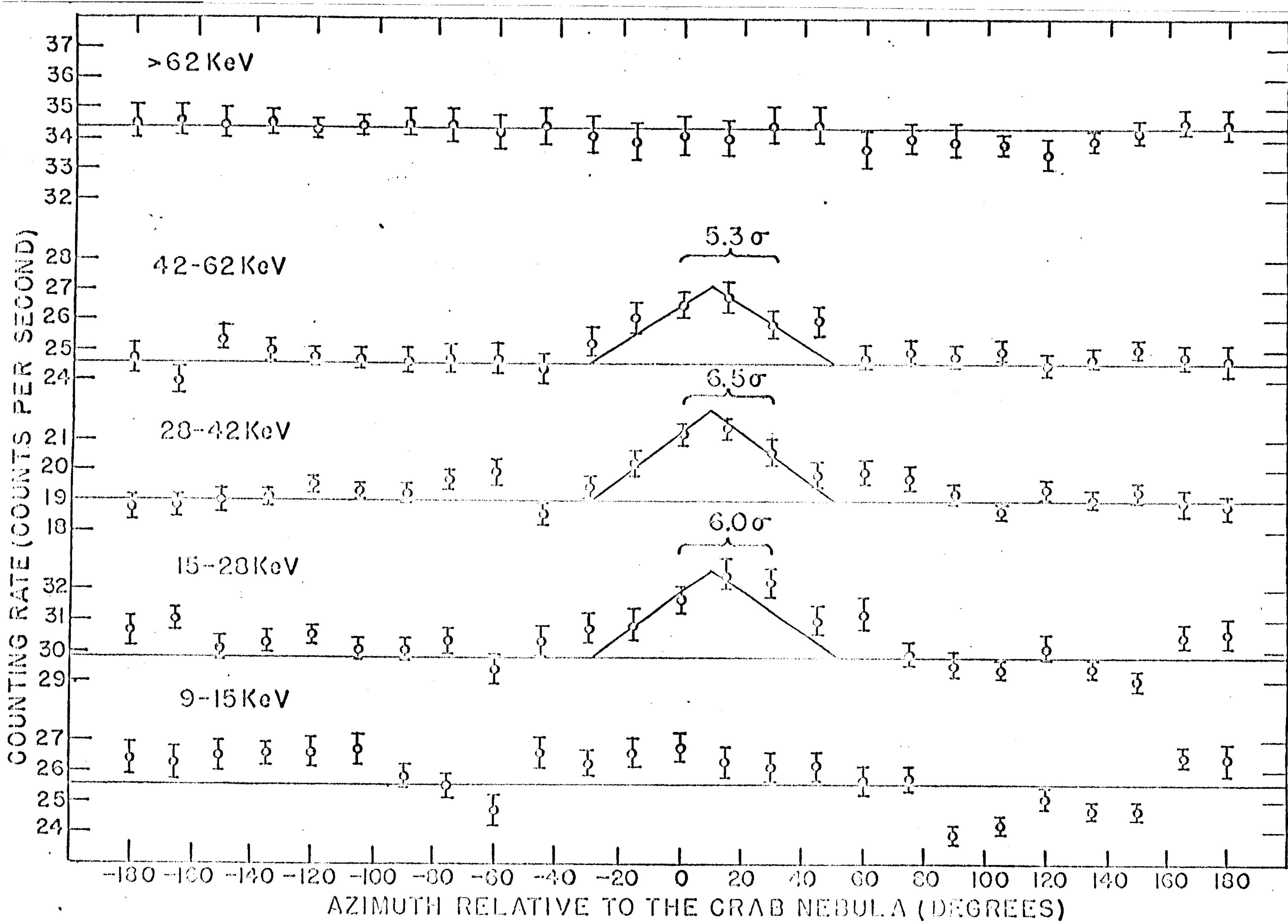

Figure 1. COUNTING RATES VERSUS AZIMUTH RELATIVE TO THE CRAB NEBULA

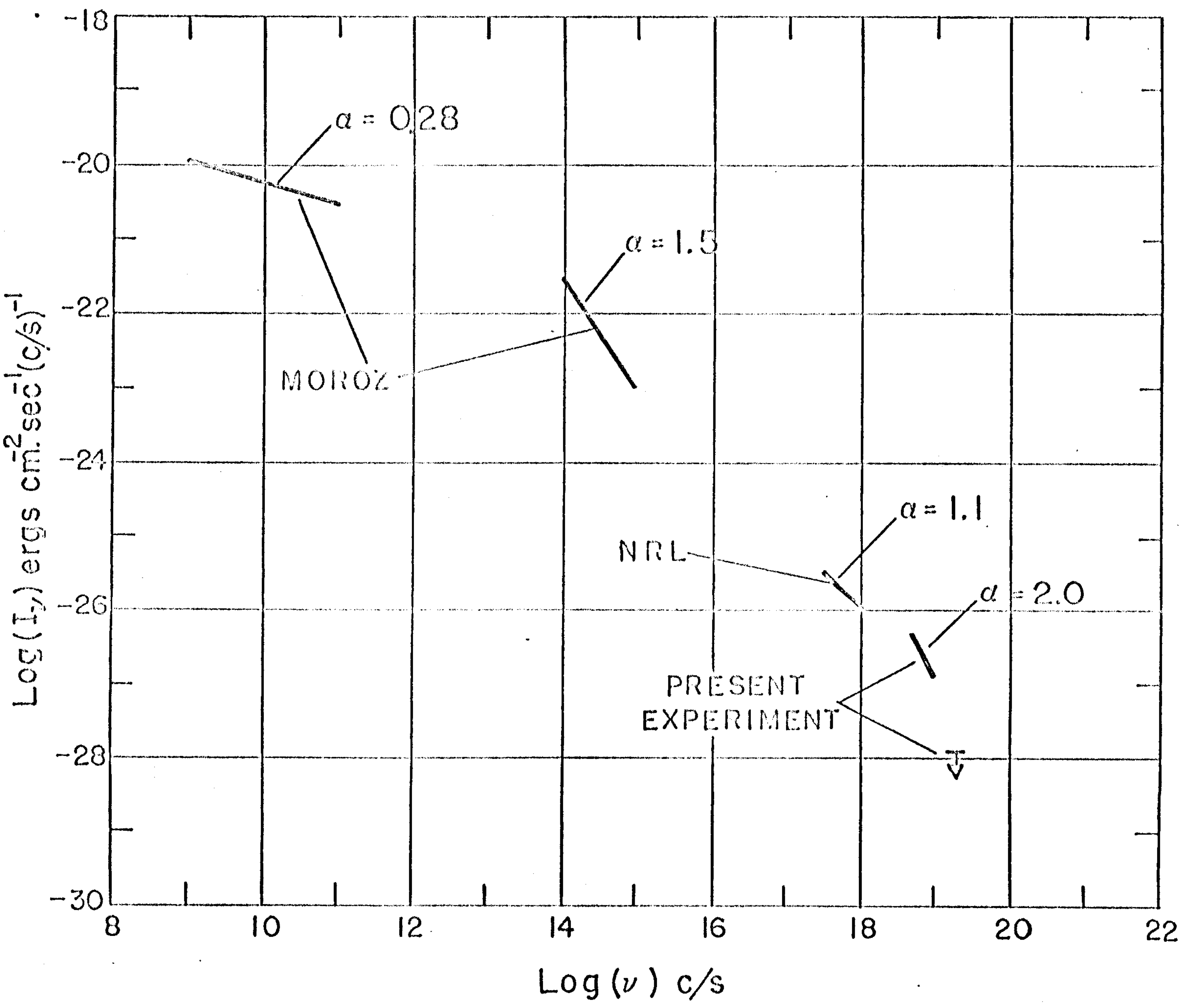

FIGURE 3. SUMMARY OF DATA ON THE ELECTROMAGNETIC SPECTRUM OF THE CRAB NEBULA